Chapter 6

Measurement and Communication Technology

A stability controller addressing global objectives needs a reliable source of global information. Local signals may prove inadequate for this, even when reinforced by extensive modeling studies. Fortunately, not all remote signals are equally vital to controller performance, or equally difficult to transmit reliably.

It's useful to distinguish among:

- *Modulation signals* used to directly shape the controller output, u(t)
- *System status flags* used in
  - rule-based control laws (e.g., parameter scheduling)
  - coordination with other controls
  - remote controller supervision
- *Secondary response signals* for
  - direct testing of power system dynamics and controller effects
  - local monitoring of controller performance
  - alternate or supplemental modulation signals

Requiring that all modulation signals be local can make controller siting a difficult robustness issue [6-1,6-2]. There are many aspects of the controller environment which cannot be predicted from model studies, and which may not be measurable until the controller itself is available for system dynamics testing. Providing the controller (and the control engineer) an ample reserve of directly measured dynamic information can increase controller performance and robustness.

The Bonneville Power Administration (BPA), through long involvement in stability control projects, has conducted numerous measurements of system dynamics [6-3–8]. This has produced many examples of apparently anomalous system behavior. Most have been attributable to the power system itself. Some, however, may have involved false outputs from the transducers being used, or from the sensors (instrument transformers) that provide inputs to those transducers. Other likely sources include communication channels and secondary control loops, especially those in which modulation or sampling processes can translate signal components from one frequency to another.

False measurements will, at best, produce an erroneous view of the power system. This can readily lead to inappropriate engineering or operational decisions. The situation is more serious when false measurements enter the modulation loop of a major control system (Figure 6-1). It's likely that any extraneous signals emitting from the transducer will be amplified by the actuator and re-injected into the power system. This is, at best, a source of undesirable noise disturbances. It's also a potential path for disruptive interactions between the actuator and dynamic processes other than those targeted for control. The trend toward fast power electronic actuators, together with more aggressive control objectives, have sharply increased the risks in this respect.

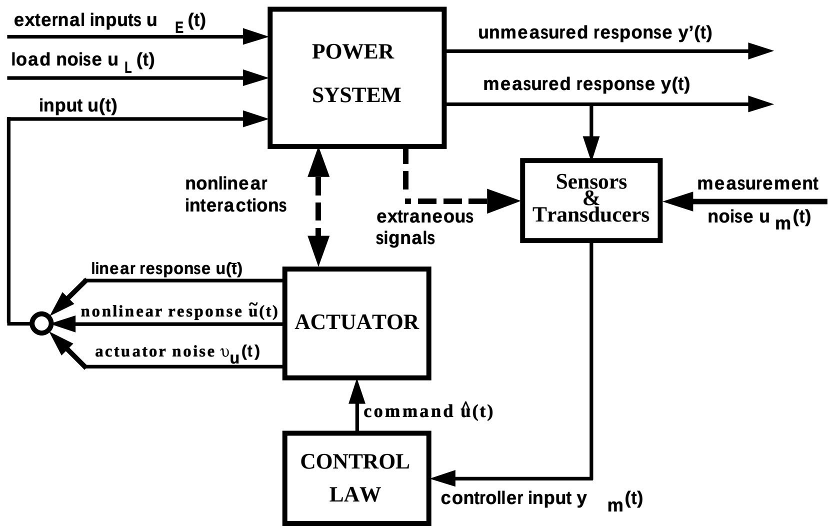

Fig. 6-1. Transducer effects in a closed loop controller.

Most stability controls seek to influence generator "swing" activity, or else the voltage support that the generators provide to the transmission network. The dynamics under control rarely occur at bandwidths above 2 Hz. The actuator, and the control law driving it, may very well have bandwidths higher than this. HVDC links and SVCs, for example, may have controllable responses up to 20–25 Hz. This encourages the use of "high speed" transducers with bandwidths in this same frequency range, to obtain full actuator performance. It also mandates the use of such transducers in monitoring of controller performance.

The vast majority of the transducers now in service are analog devices with bandwidths in the range of 1 to 2 Hz. Advanced designs can achieve bandwidths approaching 30 Hz, in principal at least. Enhanced analog transducers used at the BPA have a bandwidth of 20 Hz.

Field experience suggests that the interpretation and use of outputs from these or any other transducers should be approached carefully. Transducers of all types may be subject to aliasing effects that might, for example, permit mechanical or network resonances to mimic swing dynamics. Increasing transducer bandwidth also increases the likelihood that such effects will be present in the transducer output. Table 6-1, based in part from reference 6-11, indicates that there are many candidate sources for extraneous transducer outputs.

Desired characteristics for next-generation transducers include:

- Rigorous protection against out-of-band input signals.
- Absence of processing artifacts, such as spurious outputs.
- Programmable outputs, for versatility of application.

- High resolution and bandwidth, in control applications.
- Assured high accuracy, in metering applications.
- Good networking options, both local and wide area.
- Option for synchronizing measurements against a precise external reference.
- Overall affordability, considering all cost elements.

Such transducers will almost certainly require digital technology.

Table 6-1.Extraneous dynamics in the transducer environment

Dynamic Activity	*Frequency Range -Hz*
Torsional oscillations	5 – 120
Transient torques	5 – 50
Turbine blade vibrations	80 – 250
Fast bus transfer	1 – 1000
Controller interactions	10 – 30
Harmonic interactions and resonances	60 – 600
Ferroresonance	1 – 1000
Network resonances	10 – 300

6.1 Introduction to Transducers

For our immediate purposes a transducer is a signal processing device that translates instantaneous “point on wave” current and voltage signals into averaged measures of electrical behavior. Chief among these are rms (root mean square) voltage, rms current, rms power, waveform frequency, and relative angles for voltage and current. Suitable choices among these measures—and for the averaging times used in calculating them—are determined by the information that is needed. Reference 6-12 provides an overview of standard transducer types.

Existing transducer technology reflects a broad range of information needs. The slow end of the spectrum is occupied by revenue meters, which sacrifice dynamic response for high reliability and accuracy. At the other extreme, a digital relay is designed to detect and assess dynamic events with no more accuracy than reliability demands. Transducers for stability control occupy a broad middle range, contingent upon the:

- *Kind of dynamic process to be stabilized*. Possibilities include
  - local swing modes (with modulation on individual generators)
  - interarea swing modes (with modulation on HVDC or FACTS device)
  - voltage dynamics
- *Role of the transducer in the control process*. Possibilities include
  - modulation signal for feedback control

- monitoring of power system conditions and behavior
- monitoring of controller activity, especially anomalous interactions

The transducer for a feedback modulation system would, by choice, be equipped with internal and external filters protecting the feedback loop from interactions with extraneous dynamics. By contrast, a transducer for monitoring controller performance should be capable of *detecting* such extraneous dynamic activity. It would probably be more lightly filtered, and it might have a bandwidth approaching 25 or 30 Hz. If interactions are sensed at such frequencies it is highly desirable that direct waveform recordings be made on a local digital fault recorder (DFR) or similar device. Figure 6-2 provides an example of current waveforms under moderately disturbed conditions [6-13].

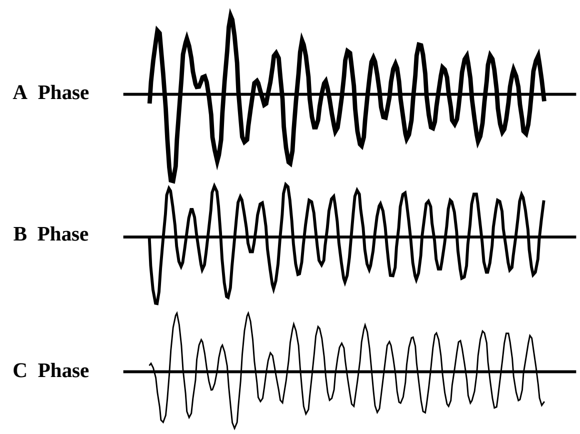

Fig. 6-2. Measured current at Olinda substation for COTP Test Fault #3 (1715 h on 03/23/93).

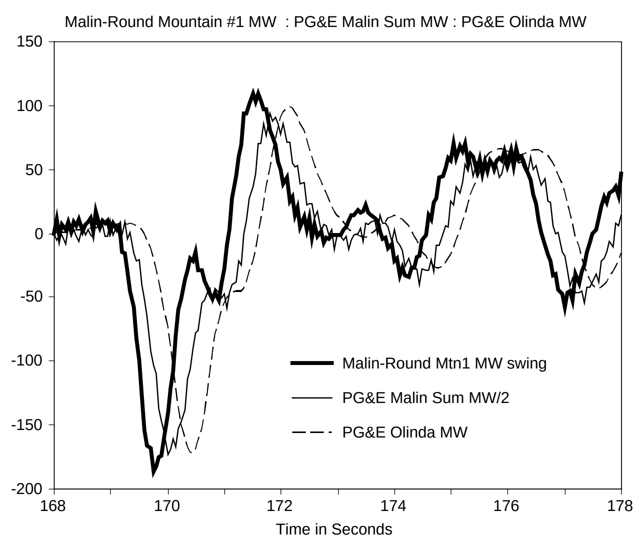

Fig. 6-3. Time response of Malin area transducers, insertion of Chief Joseph dynamic brake on August 10, 1996.

Figures 6-3 through 6-5 indicate the relative performance of three kinds of transducers, as observed through the microwave channels that communicate their outputs to BPA's control center. All three transducers measure components of the real power export to Pacific Gas & Electric (PG&E) on the California – Oregon Interconnection, or COI. The signal for Malin – Round Mountain circuit 1 is taken from an enhanced analog transducer that has a bandwidth of 12–14 Hz, and that communicates on a 20 Hz channel. At the other extreme, the transducer for the PG&E – Olinda exchange is a conventional analog transducer communicating through a low-bandwidth channel (probably 1.5 Hz or lower).

Differences among the signals in Figure 6-3 are almost entirely due to the instrumentation. Ignoring transducer/channel dynamics, the PG&E – Malin signal should be very close to twice that for Malin – Round Mountain circuit 1, and the PG&E – Olinda signal should be very similar except for magnitude. It is apparent that much of the waveform detail is not tracked very well by the slower instrumentation, and that the waveforms also exhibit appreciable delays.

Quantitative measures of relative response can be obtained by correlating the transducer signals against one another. Figure 6-4, based upon ambient noise outputs, compares the slowest signal against the fastest. Since the fast transducer has a much higher bandwidth (e.g., its response is nearly flat to well past 1 Hz), it appears that the much slow Olinda transducer has a -3 dB bandwidth near 0.9 Hz. Its relative time delay, evident in the linear phase characteristic which produces a lag of 180 degrees near 0.85 Hz, can be estimated as (180)/(360*0.85) = 0.59 second. This value is consistent with Figure 6-3, but more accurate than what would be obtained by direct inspection.

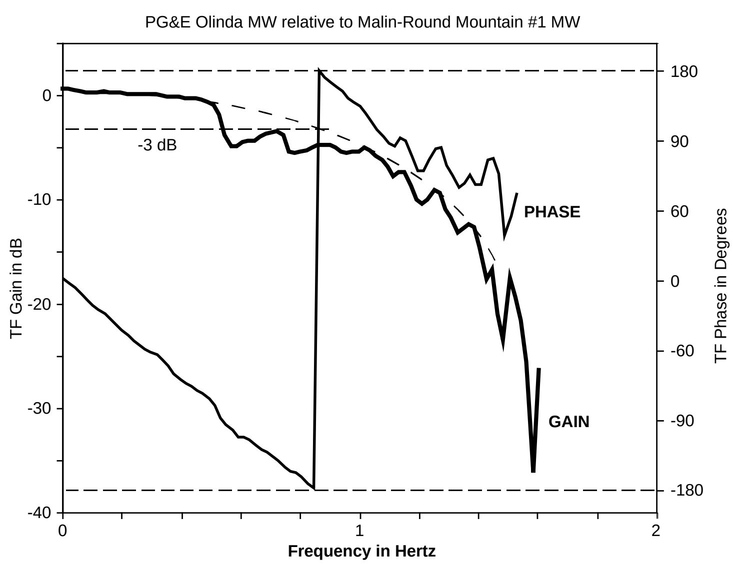

Fig. 6-4. Olinda transducer response relative to Malin transducer.

These differences in bandwidth and transient performance are not always evident, or major handicaps, in other forms of analysis. Figure 6-5 shows that all three transducer signals produce useful and consistent spectral characterizations for important WSCC swing modes up to perhaps 1.4 Hz. Amplitude differences for the spectral peaks can be corrected through knowledge of the transducer filtering and channel response, as can some of the phase and timing differences. Such corrections add considerably to computational demands and staff workload, however, and they are rarely possible in an on-line environment. It's better to avoid them through use of quality instrumentation.

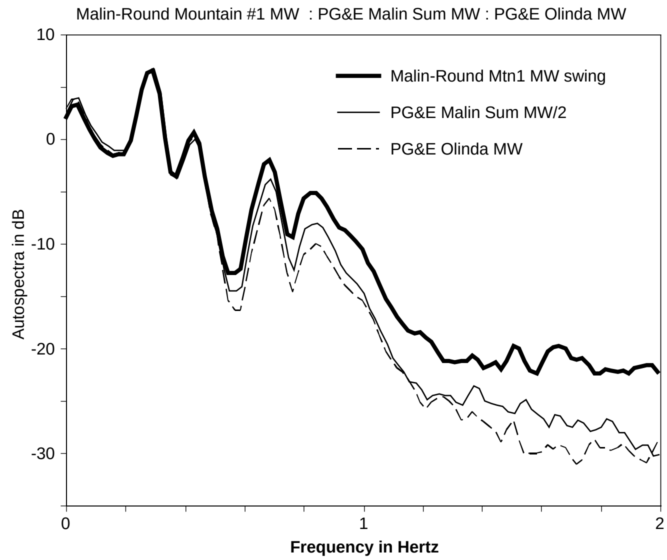

Fig. 6-5. Ambient noise autospectra for Malin area transducers

6.2 The Signal Environment for Power System Transducers

A power system transducer is intended to extract information that has been impressed upon a set of fundamental-frequency (e.g., 60 Hz) carriers by a combination of amplitude modulation and frequency modulation. In the simplest cases the transducer will have just one input. At the other extreme, a rms transducer for real or reactive power may have as many as 3 voltage and 3 current signals as its inputs. There is no assurance that their underlying 3-phase carriers will be balanced, even during steady operation. For this and other reasons, determining the physical significance of system activity may necessitate decomposition of the signals into "symmetrical components" plus accessory filtering specific to their application.

The input signals may also contain components produced by mechanisms other than modulation of the fundamental frequency carriers (Figure 6-6). These include:

- modulated harmonics of 60 Hz
- extraneous carriers (not necessarily at harmonics of 60 Hz)
- modulated extraneous carriers
- additive transients.

Reference 6-11 surveys physical sources for such extraneous components.

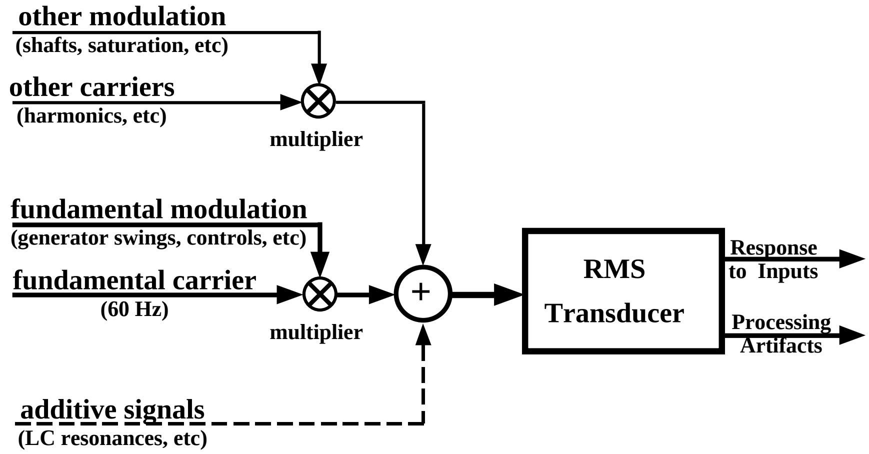

Fig. 6-6. Signal environment for a power system transducer.

The most likely sources of frequency aliasing seem to be amplitude modulation, system frequency offsets, and digital decimation. Amplitude modulation can affect both analog and digital transducers. The governing relations are simple:

$$\sin(x)\sin(y) = \tfrac{1}{2}[\cos(x-y) - \cos(x+y)] \tag{6.1A}$$

$$\sin(x)\cos(y) = \frac{1}{2}[\sin(x-y) + \sin(x+y)] \tag{6.1B}$$

The following examples show some consequences of these relations (see also Appendix D):

a) 1 Hz modulation of a 60 Hz carrier produces waveform components at 60±1 Hz (i.e., at 59 Hz and at 61 Hz).

b) Re-modulation of the above waveform produces components at ±1 Hz and at 120±1 Hz. Then the original modulation can be recovered by lowpass filtering.

c) 30 Hz modulation of a 60 Hz carrier produces waveform components at 30 Hz and at 90 Hz.

d) 30 Hz modulation of a 120 Hz carrier produces waveform components at 90 Hz and at 150 Hz (overlapping case c).

e) Squaring any of the above waveforms produces terms at 0 Hz.

This provides a number of ways in which a signal might enter a transducer at one frequency and be shifted to another. Those based upon amplitude modulation are discussed more thoroughly in reference 6-14. Sampling effects in digital transducers considerably expand the possibilities for frequency aliasing.

Field observations confirm that transducers operate in a very demanding signal environment. On April 24, 1996, direct measurements were performed on enhanced transducers at BPA's Slatt substation [6-15]. Figures 6-7 through 6-9 show a sequence of autospectra for A-phase current, as determined with a Scientific Atlanta SD390 4-channel dynamic signal analyzer. Related theory is available in [6-16–18]. In Figure 6-7 the peaks near 28 Hz and 92 Hz are probably associated with a modulating source at 32 Hz (very likely a generator shaft). These spectra are in close agreement with MATLAB analysis of signals extracted from the BEN 5000 digital fault recorder at Slatt, and voltage spectra were similarly complex. Corresponding transducer spectra are shown in a later section.

Figure 6-10 extends the observations made at Slatt substation. The spectrum in this figure was obtained at Big Eddy substation, which is directly connected to the Celilo converter of the Pacific HVDC Intertie (PDCI). The PDCI was deliberately operated in a high harmonic configuration in order to test transducer performance [6-19]. The numerous spectral peaks, many not at integer harmonics of the 60 Hz power frequency, further indicate just how harsh the transducer operating environment can be.

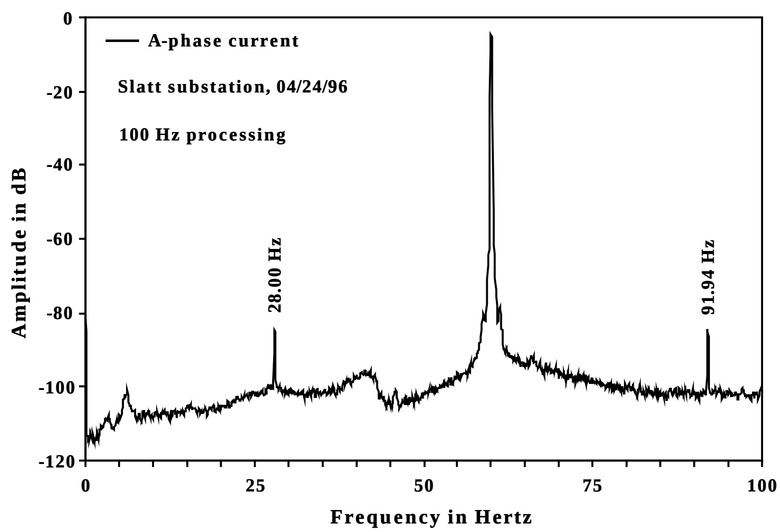

Fig. 6-7. Autospectrum for A-phase current. Slatt Substation, 04/24/96.

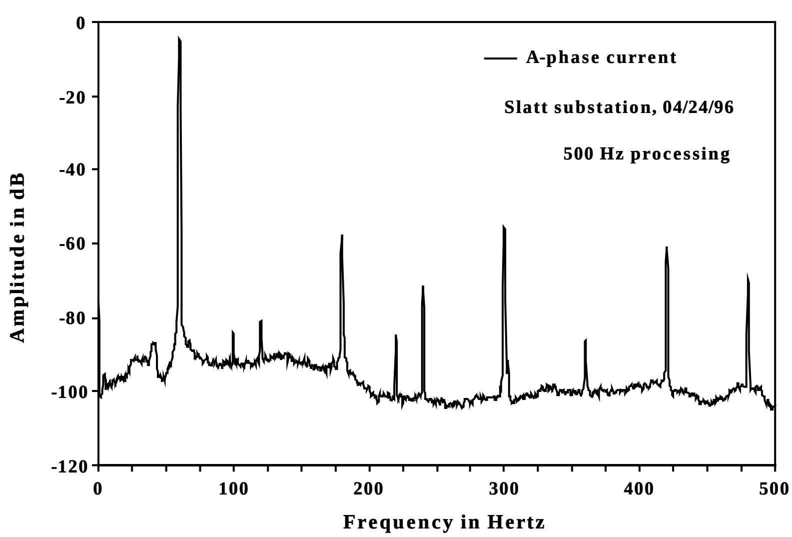

Fig. 6-8. Autospectrum for A-phase current. Slatt Substation, 04/24/96.

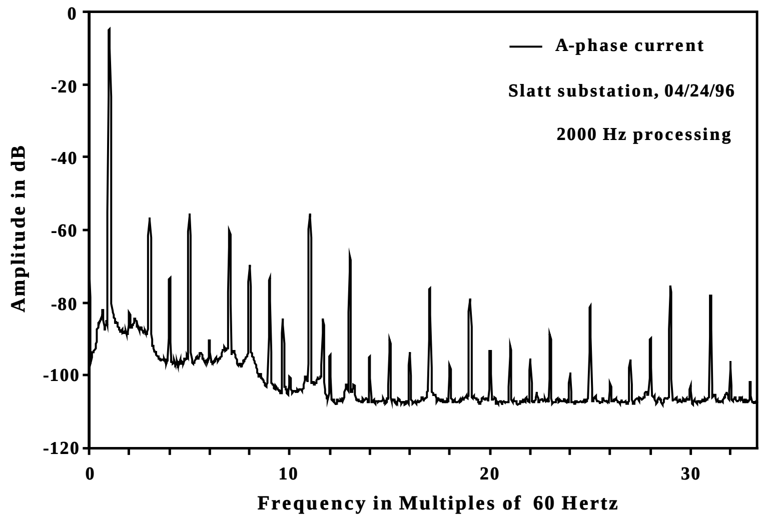

Fig. 6-9. Autospectrum for A-phase current. Slatt Substation, 04/24/96.

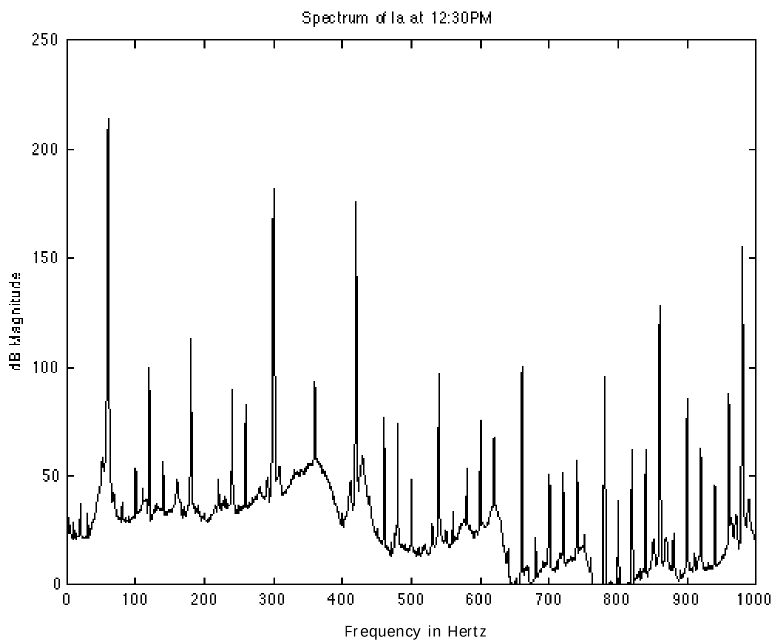

Fig. 6-10. Autospectrum for A-phase current, HVDC controls in high harmonic configuration. Big Eddy Substation, 10/25/96.

Figures 6-11 and 6-12, showing frequency records for individual islands formed during WSCC breakups in 1994, indicate that protracted operation at anomalous frequencies is another challenge to transducer performance. In the case of Figure 6-11 the island frequency remains below 59.9 Hz for roughly 25 minutes. It’s possible that transducers not designed for such operation would experience filtering or timing problems under such conditions, and produce spurious outputs.

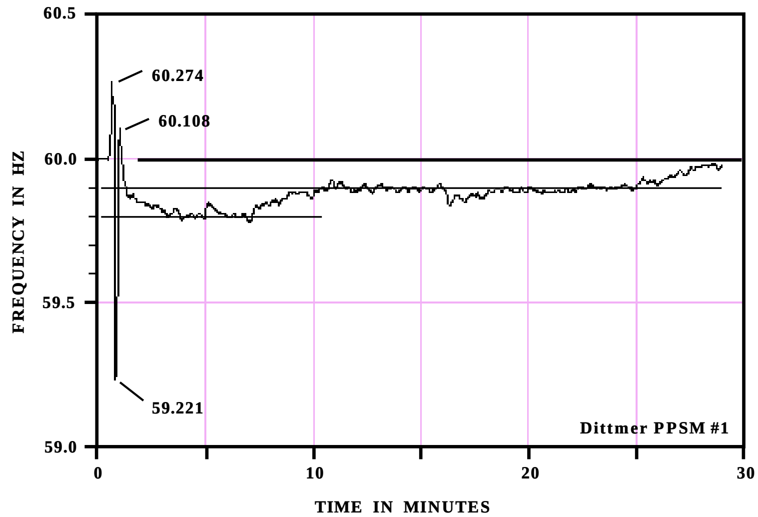

Fig. 6-11. BPA system frequency following Los Angeles earthquake of January 17, 1994 (BPA control center, Vancouver, Washington).

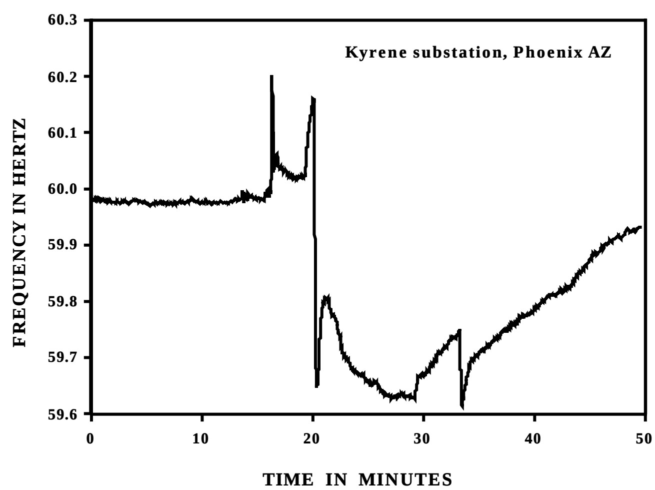

Fig. 6-12. Phoenix, Arizona area system frequency following WSCC breakup of December 14, 1994.

6.3 Signal Processing in Power System Transducers

Let v(t) and i(t) denote the instantaneous voltage and current signals that are processed within a particular transducer. We will consider a transducer to be of analog type if all of its output signals are analog, but digital if some or all of its outputs are in the form of multi-level digital data.

Transducers can be categorized, a bit cavalierly, into:

- *“Algebraic” or “point on wave” transducers* that perform simple calculations upon v(t) and i(t).

- *Phasor transducers* that project v(t) and i(t) onto reference waveforms, thereby generating associated voltage and current phasors that are used in all further calculations (see Figure 6-13).

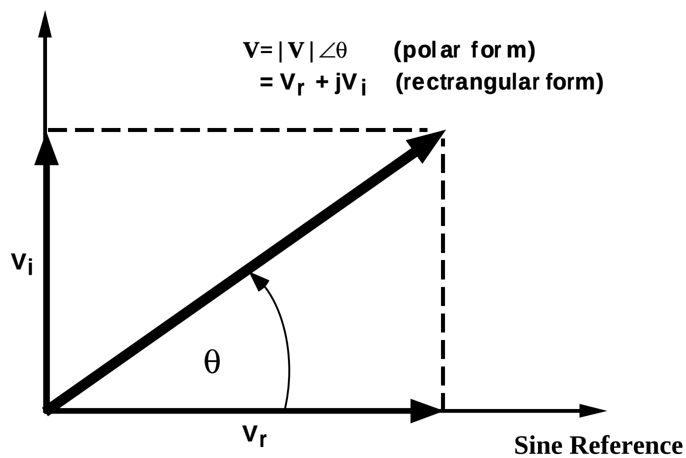

Fig. 6-13. Phasor determination via projections.

The associated logic can be organized in many different ways, and specific hardware products may well contain some for each category. Whereas algebraic transducers may be either analog or digital, contemporary phasor transducers appear to be entirely digital.

The processing in Figure 6-14 is representative of modern analog transducers that BPA uses to measure real and reactive power. The voltage input width modulates a train of square pulses, which is then amplitude modulated by the current signal. The two kinds of modulation, PWM followed by AM, constitute an analog multiplier circuit and yield a signal that is pulse-ratio modulated (PRM). Filtering requirements are greatly reduced by first combining the PRM signals for all three phases.

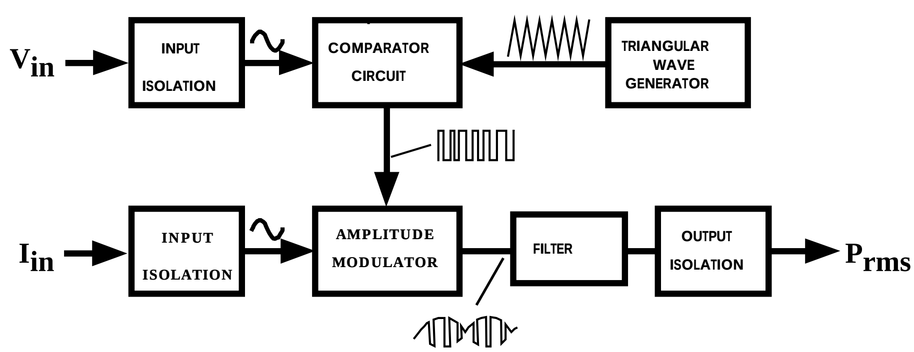

Fig. 6-14. General architecture for a pulse ratio modulation (PRM) megawatt transducer.

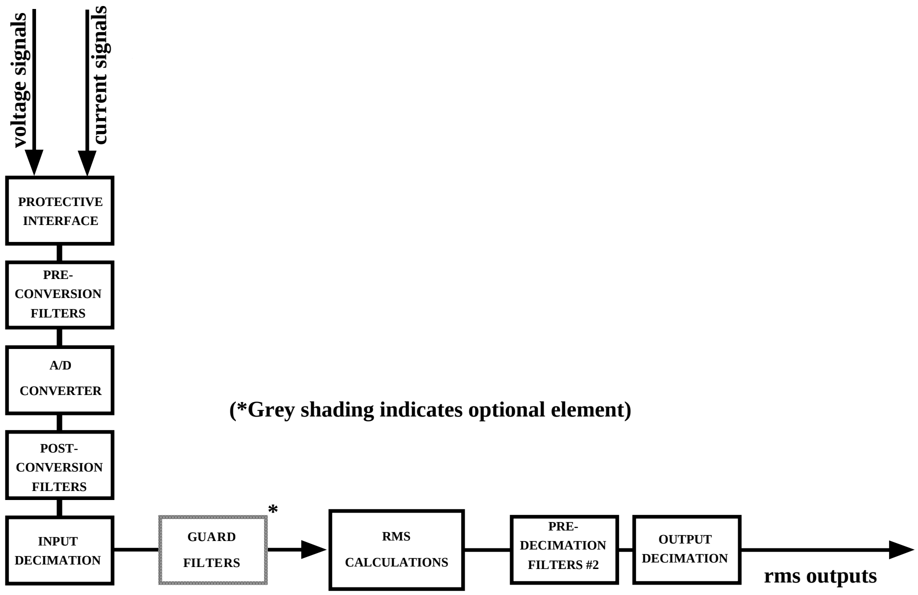

Fig. 6-15. General architecture for an algebraic digital transducer.

Figure 6-15 represents the functional organization (showing just one phase) for an algebraic digital transducer. This is extended in Figure 6-16, which is broadly representative of digital transducers based upon phasor calculations. The structure provides several points where bus frequency can be estimated, and it permits use of this estimate to adjust the reference signals upon which voltage and current signals are projected.

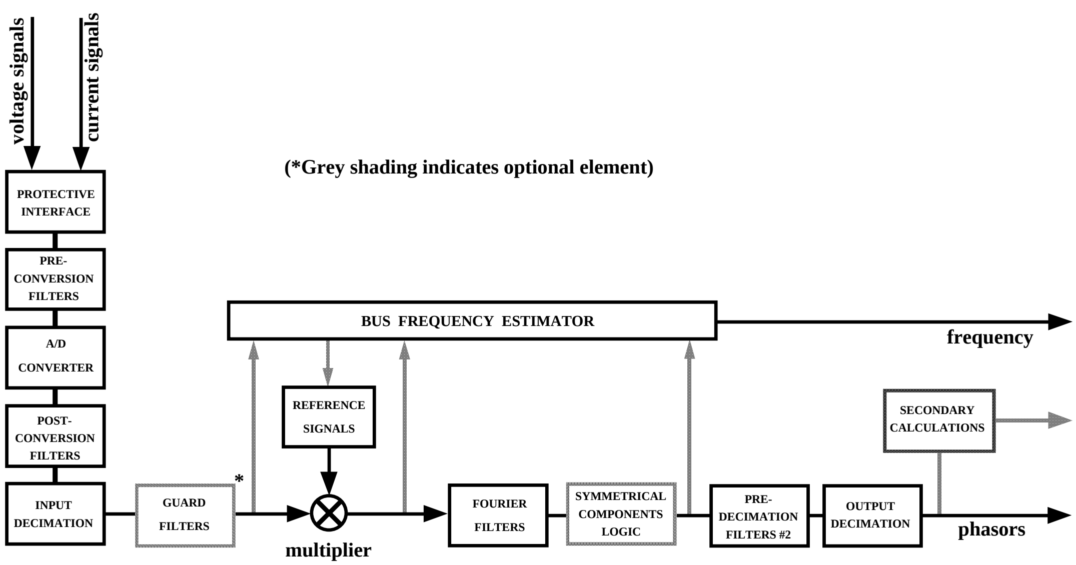

Fig. 6-16. General architecture for a phasor transducer.

Among the other optional features in Figure 6-16, the guard filters warrant special mention. While their function might actually be absorbed into the post-conversion or the

Fourier filtering, the appropriate settings may change with the application. This is particularly likely in high performance stability control, where both the control law and the monitoring equipment should be well protected against spurious activity.

The signal processing in a phasor transducer is directly based upon Fourier analysis, and much the same as that used in a dynamic signal analyzer. See also Appendix E.

6.4 Criteria and Procedures for Evaluating Transducer Performance

Distinctions are made here between the following kinds of transducer performance:

- *metering performance*. Emphasis upon precise measurements under normal system conditions, network condition monitoring.
- *Small-signal dynamic performance.* Emphasis upon feedback control and interactions monitoring.
- *Large-signal dynamic performance*. Emphasis upon remedial action (feedforward) control, disturbance monitoring.

Technical performance factors in control applications are resolution, bandwidth, delay, accuracy, noise, protection from aliasing, other filtering considerations, and transient behavior. The proposed test procedures will focus upon small-signal dynamic performance, which is critical in those applications having the greatest exposure to parasitic interactions.

Distinctions are also made between kinds of information to be obtained from transducers in a control environment. As illustrated in Figure 6-17, the output of a transducer that is used to track large signal dynamics might also be low-pass filtered to display slow trends and high-pass filtered to display small-signal activity. This assumes, of course, that signal processing within the source transducer is fast enough to track large signal dynamics in the first place.

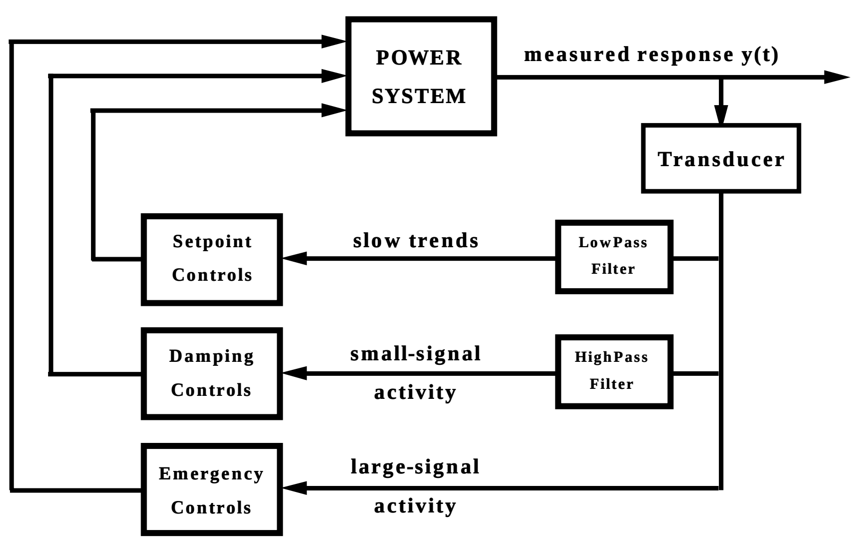

Fig. 6.17. Allocation of transducer signals in power system control.

The criteria for evaluating transducers in control applications are necessarily different from those used in static or slowly changing measurements. The following are recommended as high priority performance targets in control applications:

a) *Bandwidth:* in the range of 10–25 Hz, the higher the better.

b) *Resolution and dynamic range:* equivalent to 14–16 bits.

c) *Delay:* must be essentially constant, not to exceed 30–45 degrees within the primary control band.

d) *Carrier filtering* (including harmonics): carrier effects will likely be visible to sophisticated analysis, but must be outside the nominal bandwidth of the transducer and small enough to remove through accessory filtering.

e) *Harmonic modulation:* information imposed upon power frequency harmonics above the first must be outside the nominal bandwidth of the transducer, and small enough to remove through accessory filtering.

f) *Positive sequence response:* transducers intended to respond just to positive sequence activity should perform accordingly.

g) *Off-frequency performance:* the above criteria (a–f) should be met during sustained ramps and offsets of system frequency.

h) *Unbalanced operation:* the above criteria (a–f) should be met during sustained unbalances of three phase voltage and/or current.

The following are recommended as lower priority performance targets for control applications:

i) *Accuracy:* something on the order of 0.5% of reading is usually sufficient.

j) *Fixed offset:* usually measured, and often removed by highpass filtering.

k) *Drift:* often removed by highpass filtering. If drift is substantial, it must not vary so rapidly as to mimic power system activity.

l) *Instrument noise:* must not have strong peaks within the primary control band, and must be small enough to remove through accessory filtering.

It should be noted that no criteria are recommended for discriminating between additive signals on the power system (such as network resonances) and signals associated with carrier modulation. Desirable as such a capability would be, it’s unlikely that existing transducers can provide it.

Appendix F describes laboratory evaluation of transducers and Appendix G describes field evaluation of transducers.

6.5 Transducer Modeling and Simulation

Laboratory tests and field examination of transducer performance have been reinforced through the use of computer models. The general approach involves:

- Use of SPICE computer software [6-21,6-22] to examine interface and circuit performance.
- Use of MATLAB computer software [6-23] to examine the generic signal processing

Models were developed for the (analog) PRM megawatt transducer of Figure 6-14, plus digital megawatt transducers of both algebraic and phasor types (Figures 6-15 and 6-16). The MATLAB codes permit direct changes to signal processing parameters, such as filter type and settings, and they support a broad menu of test waveforms.

Appendix H provides results of transducer modeling and simulation, and related analysis.

6.6 Digital Transducers and Phasor Measurements

The chapter introduction listed desired characteristics for next-generation transducers. This section assesses available products having potential for advanced stability control.

As the term is used here, the distinguishing characteristic of phasor technology and phasor transducers is the explicit calculation of the phasors themselves. Apart from the special values that phasors themselves may have in stability control, it's clear that any technology capable of calculating them is a good candidate for developing better transducers. It's equally true that any well-filtered algebraic digital transducer can probably be converted into a phasor transducer.

It's also apparent that that the desired class of transducers represents a functional extension of the conventional technology, not just an improvement. A transducer that is directly networkable, and that performs measurements in synchronization with some precise global reference, can be neither developed nor evaluated without considering its role in the overall measurement network. Also, by using the global reference in the phasor projection, all phasors in the network provide consistent angle information. The essential integrity of phasor processing, however, is valuable even when global phase angles are not produced.

The WAMS project [6-10] assessed the several digital transducers.

Macrodyne Phasor Measurement Unit (PMU) [6-24–26,6-37]. Considered as an individual device, this is a phasor transducer plus:

- Optional synchronization against precise time references.
- An evolving interface for direct local networking.
- Local recording capabilities as a basic "snapshot" monitor.

General performance features of the PMU include:

- An input sample rate of 12 samples per cycle (720 samples per second at 60 Hz) after prefiltering, with 16 bit digitization. All sampling is referenced against nominal system frequency, not actual.
- Output sample rates of 30, 12, and 6 samples per second, user-selectable.

- Voltage and current positive sequence phasors and bus frequency as standard outputs; quantities such as rms power or apparent resistance must be calculated later.

The PMU is expressly designed to operate in wide-area networks. Operational details and observed performance are described in [6-13,6-25,6-27,6-37].

7700 ION Programmable Transducer System, produced by Power Measurement Ltd. (PML) [6-28]. The 7700 ION (Integrated Object Network) functions as a high bandwidth algebraic digital transducer and, at a lower output rate, as an FFT-based harmonic analyzer.

General performance features of the 7700 ION include:

- Input sample rate of 128 samples per cycle (7680 samples per second) after prefiltering, usually with 12 bit digitization. All sampling is referenced against a fast running estimate of system frequency.
- Output sample rates ranging to 60 samples per second, according to type and user selection.
- A very wide range of rms outputs, programmable by the user. Present logic provides voltage and current phasors at low rates only, via the harmonic analysis and using a local reference.

The ION 7700 is highly evolved for operation in local area networks, which include central recording plus modem connections into wide area networks.

The Dynamic System Monitor (DSM), produced by Power Technologies Inc. (PTI) [6-29]. In this case phasor transducer logic is imbedded into a general purpose monitor. General characteristics of the DSM's transducer include:

- An input sample rate of 4 samples per cycle (nominally 240 samples per second) after prefiltering, with 16 bit digitization. All sampling is referenced against a running estimate of system frequency.
- An output sample rate of 1 sample per cycle, which the user can decimate under program control.
- A very wide range of rms outputs, programmable by the user. Voltage and current phasors can be obtained for the same global references that are accessed by the PMU.

The DSM is primarily designed to operate independently, but with modem connections into wide area networks.

While new digital transducer technology is appearing on the market with increasing frequency, the three devices above are well established in the field and thereby of special interest. They are also different enough in their processing details to span a good range of the basic possibilities. Evaluating these devices—or, more precisely, the technology approaches that they represent—remains an ongoing process.

6.7 The Transducer as an Intelligent Electronic Device

We have shown that transducers and transducer logic take many different forms, and are combined into products with different functionality combinations. In short, the term "transducer" no longer has very explicit meaning when the base technology is digital. The Macrodyne PMU is an outstanding case of this. It's a transducer for producing rms signals, a simple monitor, and a building block for wide-area measurement networks. At another extreme, it is not unusual for a modern excitation controller to contain transducer logic within a digital control law. Similar logic, sometimes in optical form, is also appearing in such mundane devices as electrical bushings and circuit breakers.

It can be misleading to call several different things "transducers" when the functionality they offer are so diverse. Similar problems are encountered with power system monitors, controllers, and even the sensors that provide signals to higher levels of the measurement system. There is a useful trend now to just designate any such device as an "intelligent electronic device," or *IED* [6-28,6-30].

From this perspective a wide-area measurements network is an integrated structure of IEDs, with sensing and transducing logic occupying the lower hierarchies. Selecting IEDs with the right functionality combinations lies at the heart of the value engineering process.

6.8 Role of Communication Channels in Wide-Area Control

A fully evolved stability controller for wide area dynamics requires access to signals of the following kinds:

- *modulation signals* used to directly shape the controller output u(t).
- *system status flags* used in
  - rule-based control laws (e.g., parameter scheduling)
  - coordination with other controls
  - remote controller supervision
- *secondary response signals* for
  - direct testing of power system dynamics and controller effects
  - local monitoring of controller performance
  - use as alternate or supplemental modulation signals

Signals are also required from the controller to operation centers, and perhaps to other locations, where its status and performance are supervised and coordinated with those of other controls.

The signals used as modulating inputs are the most demanding in terms of quality, reliability, and security. These needs are most easily met if the signals are produced locally to the controller site. Requiring this in advance, however, can make controller siting a difficult robustness issue. There are many aspects of the controller environment which cannot be predicted from model studies, and which may not be measurable until the controller itself is available for system dynamics testing.

Channels for modulation signals can, superficially, be categorized as analog or digital. For this discussion, an analog channel is one that accepts an analog signal as an input and carries the signal in large part as a continuously varying analog signal. Analog channels usually offer the advantages of high bandwidth relative to that of the measured signal, minimal communication delay, and reasonable immunity to undetected tampering. They also tend to be noisy, and maintenance intensive. Digital channels, by contrast, involve a conversion of the signal to digital format and a commensurate increase in delay. They also have a lower signal bandwidth for a given channel bandwidth but require less channel calibration. The digital format also allows noise free data recovery and positive verification of data integrity.

While digital channels do not experience “noise” in the same sense as analog channels, they have a counterpart in occasional message loss. This calls for some kind of data repair, analogous to noise filtering in analog technology. At present, digital communications may also be more expensive than analog for the same bandwidth. Modems, if present, introduce communication delays and expose the information system to penetration by unauthorized persons.

At the very lowest level, all communication systems are analog in the sense that the physical processes can assume an infinite number of states. At higher levels, digital communications modulate analog processes between a finite number of states (often just two states) that the detection logic is designed to recognize. Distortion and noise at the analog level can produce errors in demodulation and, thereby, in communication of digital data.

Traditional analog communications take an analog signal from a transducer and transports it as a continuously present and continuously varying voltage, current, phase shift, or frequency shift. There are no delays other than those produced by distance and by filter effects. There are few artifacts in the information equivalent to the aliasing and quantizing errors sometimes introduced in digital systems. Means for separating noise components in the signal from the information are less effective, though, and it is more difficult to detect dropouts. Channel gains and offsets directly enter the received signals, so analog channels require frequent and precise calibration to maintain accuracy.

Modern communications frequently convert analog signals to digital quantities for long distance transmission. The transport system can be as simple as a pair of wires or as complex as multi stage exchange involving satellite, microwave, and fiber optic links. This is largely transparent to the user. But, while this hybrid approach mitigates some of the difficulties found in completely analog systems, it can also cause new problems associated with digital elements of the overall system and with digital/analog interfaces.

Telephone systems are a case in point. Once entirely analog, they have been progressively converted to digital technology, first at the backbone (long distance) level and more recently at the local level. This mixture of technologies means that data transmission over telecommunication systems may encounter one or more conversions between analog and digital formats. The earliest modems transmitted digital signals on analog links by shifting the phase or frequency of a tone that was detected as digital 0's and 1's at the other end. There was no added communication delay other than the time needed to assemble a set of binary digits into a word for processing. More sophisticated coding has now been developed to make better use of the (analog) channel capacity. The result is more digital capacity, but at the expense of increased processing delay. To maintain the high data rate modems must "train" with each other to reduce errors. In doing this they monitor communication errors and re-train if the errors increase unduly. This can cause an unanticipated break in communication service. Breaks can also occur through data re-transmission commanded by error detection logic.

Problems aside, the issue is not digital technology versus analog. Rather, the issue is how to plan and manage the transition to digital technology. Appendix I describes utility experience with older analog communication channels. The following section describes utility experience, based upon observed performance of a phasor measurement system spanning a broad region of the western North American power system.

6.9 Observed Performance of Digital Communications in the BPA Phasor Measurement Network

This section shows the performance of digital communication channels within BPA's phasor measurement network. All channels are frequency division multiplexed microwave, owned and operated by BPA.

The performance data were obtained from test insertions of the Chief Joseph dynamic brake on September 4, 1997 [6-27]. Five Phasor Measurement Units (PMUs) communicated data to a Phasor Data Concentrator (PDC) located near the Dittmer Control Center in Vancouver, Washington, USA (see Figure 6-18). The PDC was developed by Ken Martin of BPA.

The PMU locations were Grand Coulee, John Day, Malin, Colstrip, and Sylmar.

The PMU at Sylmar belongs to the Los Angeles Department of Water and Power. Each PMU was configured to produce one positive sequence voltage phasor and four positive sequence current phasors at a rate of 30 samples per second (sps).

The PDC data acquired for the test consists of 23 raw data files (45 megabytes) spanning two recording intervals of roughly 80 minutes each. Most of these files contain occasional "outliers" in the data. These usually represent data packets (messages) that were lost in the digital communication system, or some brief loss of synchronism at modem level. Accessory data from the PDC indicate these defective data precisely.

Figure 6-19 indicates that these outliers often tend to be conspicuous in the signals themselves, as points very near zero. The signal, which extends across all of recording interval #1, shows just 8 outliers among 144,000 rms power calculations. It's possible that some of these represent defects in only the voltage or the current phasor, rather than both.

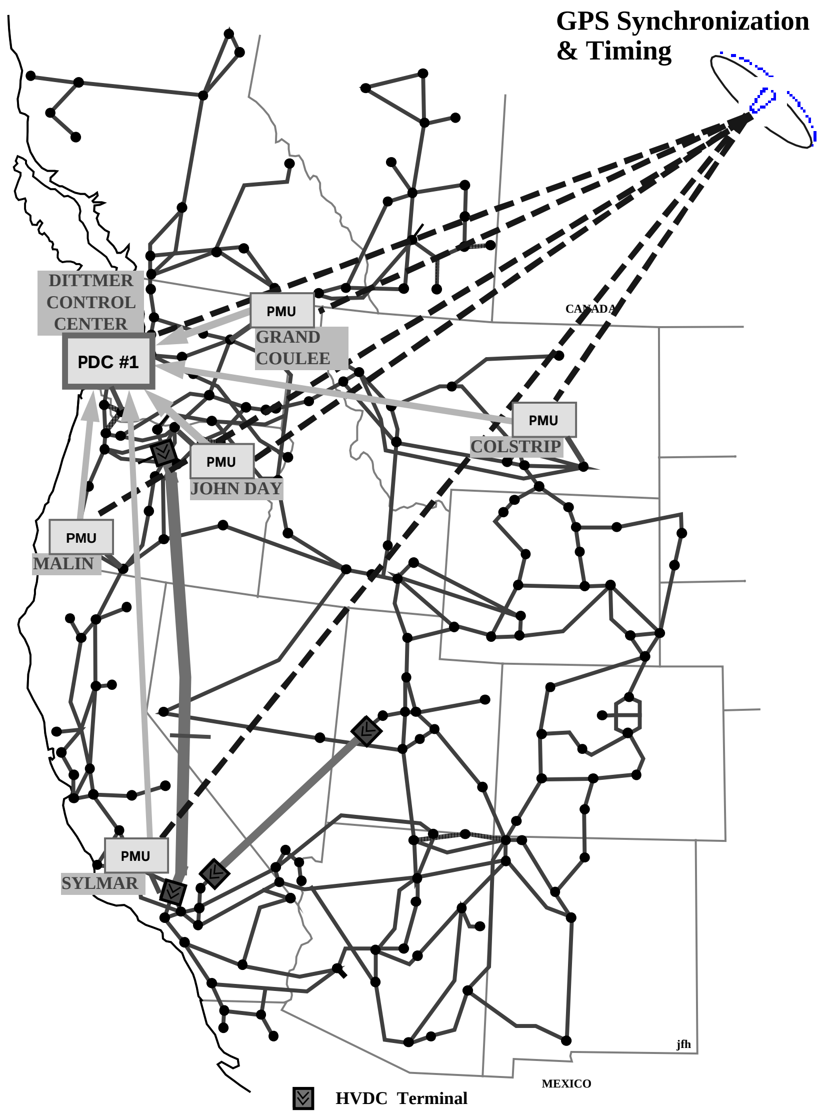

Fig. 6-18. Configuration of BPA's Phasor Measurement Network for brake test of September 4, 1997.

For analysis, outliers near zero are easily patched through linear interpolation. The signal in Figure 6-20 demonstrates that so elementary an approach is not always enough, however. In this case the repair algorithm recognized a "blank" segment of 498 points and performed a linear interpolation across it. It also recognized and repaired 5 later points (near 4000 seconds), but it is not equipped to deal with the rather suspicious data that lies between the two outlier segments that it did recognize. The source file for this record shows similar defects in all data extracted from the Colstrip PMU within this particular time frame.

Considerably more can be done to detect, flag, and (where possible) repair bad data at the signal analysis level. However, most of this is better done at PDC level, or on the basis of data validity tags produced by the PDC as accessory output. Effective standards and mechanisms for this are required at both levels.

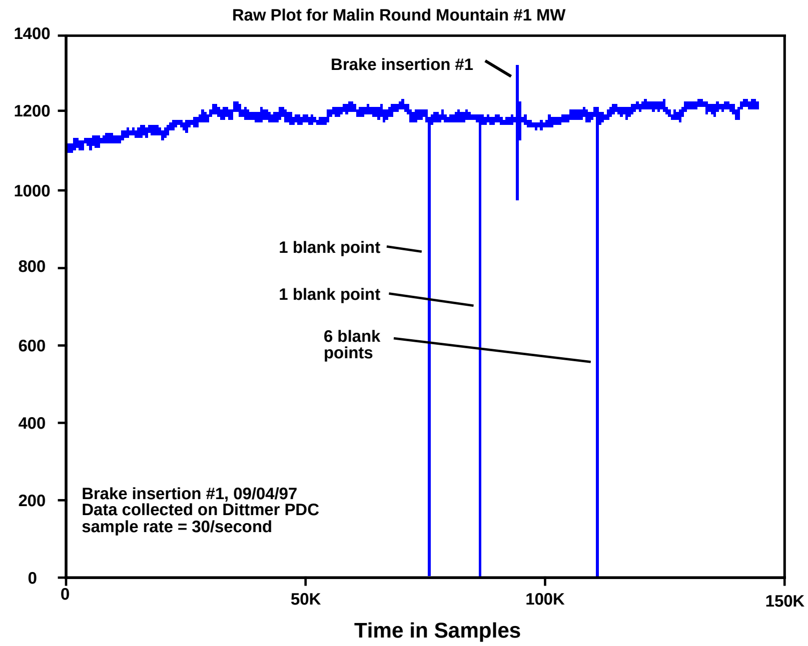

Fig. 6-19. Raw data from PDC recording segment #1.

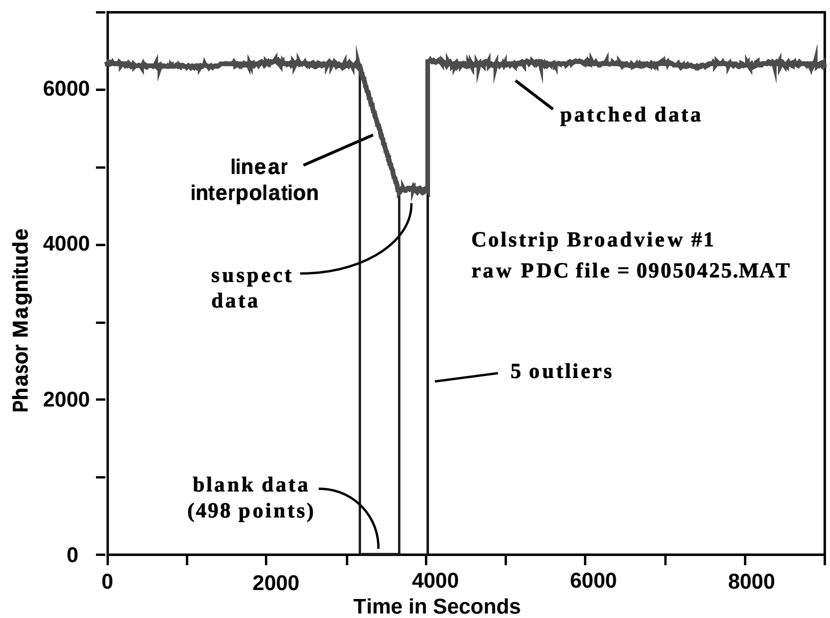

Fig. 6-20. Partial repair of a PDC file with modem retraining.

For control, detection of bad data typically causes freezing of the signal at the last good value. Sustained bad data may cause wide-area control suspension. Provisions for (degraded) local control for communication failure is normally required.

6.10 Future Digital Communication for Stability Control

Power companies and telecommunication companies are rapidly installing long distance fiber-optic communication. This is a very important development that greatly facilitates wide-area stability control feasibility. Some designs are “self-healing,” with transfer to an alternate path in 50–120 ms for a failure.

BPA has several phasor measurement links employing modems and analog microwave, and one link employing fiber optics. The measured modem/analog time delay (latency) averaged about 70 ms. The measured fiber optic link time delay was about 21 ms, corresponding to about 7° of a 1 Hz signal.

Other emerging communication techniques promise fiber optic like performance. One is low earth orbit satellites [6-34] and possibly other wireless technology. Another is digital communications over power lines. These techniques may make direct load control (e.g., heaters, air conditioners) for stability more practical. Direct load control is described in the next chapter.

6.11 Optical Sensors

The transducers described above normally use the outputs of conventional instrument transformers (magnetic current and voltage transformers, and capacitor voltage transformers). Optical voltage and current sensors, however, are commercially available from several manufacturers. Voltage and current sensors may be combined in a single device. Field evaluations have been successful [6-35,6-36].

Optical sensors may be used with digital IEDs in the substations of the future.

The advantages of optical sensors are only indirectly related to use of digital transducers for stability controls. Advantages include smaller device size and weight, elimination of hazardous oil-filled transformers, electrical isolation, elimination of substation secondary electrical cabling, elimination of instrument transformer burden limitations, wide dynamic range, wide bandwidth, high accuracy, potentially lower cost, and compatibility with digital technology.

Challenges are mainly economic, related to change out of existing instrument transformers, compatibility with legacy electromechanical relays and meters, and the volume production needed for cost reduction.

Acknowledgement: Much of the material in this chapter is based on findings of the DOE/EPRI Wide Area Measurement Systems (WAMS) project [6-9,6-10]. Material is reproduced here with the permission of BPA.

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